Bureau of Mines Report of Investigations/1986

A Statistical Determination of Spark Ignition Safety Factors in Methane, Propane, and Ethylene Mixtures in Air

By James C. Cawley

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

A	ampere	µH	microhenry
F	farad	mJ	millijoule
H	henry	µJ	microjoule
J	joule	µs	microsecond
kohm	kilohm	rpm	revolution per minute
mA	milliampere	s	second
µF	microfarad	V dc	volt, direct current
mH	millihenry	yr	year

A STATISTICAL DETERMINATION OF SPARK IGNITION SAFETY FACTORS IN METHANE, PROPANE, AND ETHYLENE MIXTURES IN AIR

By James C. Cawley[1]

ABSTRACT

The Bureau of Mines conducted an investigation to statistically determine the mean current or voltage for resistive, inductive, and capacitive circuits that would cause spark ignitions in 8.3% methane-air, 5.3% propane-air, and 7.8% ethylene-air mixtures. Each mean ignition current or voltage was determined on the basis of 100 trials. Each trial consisted of 400 revolutions, 200 in each polarity, at 80 rpm of the standard breakflash apparatus.

In general, spark ignition curves published in UL 913 for resistive and inductive circuits represent approximately the mean current values determined in this study, while published capacitive circuit values in methane are considerably less than the mean voltage values from this study, especially for a capacitance of less than 100 μF. For resistive and inductive circuits, spark ignitions were obtained at currents considerably below those in the published curves, but this study was not optimized to find minimum ignition values.

This report defines "safety factor" as applied to intrinsic safety testing as the energy ratio of the mean values of ignition current or voltage for two test gases. The safety factors presented in this report are not constant with voltage or current and, therefore, are not recommended for use.

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INTRODUCTION

In equipment approved as "intrinsically safe," any sparking in the electrical circuits that may occur during normal operation will not be enough to cause an ignition of the surrounding atmosphere. In the United States, approval of intrinsically safe apparatus used in industrial applications is based on Underwriters Laboratories Standard 913 (UL 913), "Intrinsically Safe Apparatus and Associated Apparatus," and the National Fire Protection Association Standard 493 (NFPA 493), "Intrinsically Safe Apparatus for Use in Class I Hazardous Locations and Its Associated Apparatus." The UL 913 and NFPA 493 documents are virtually identical concerning the requirements for intrinsically safe equipment. For mining applications, however, approval authority lies with the U.S. Department of Labor's Mine Safety and Health Administration (MSHA). MSHA regulations covering the approval requirements for intrinsically safe equipment for use in underground mines are contained in the Code of Federal Regulations, Title 30, Part 18.68. The MSHA document lists a short number of specific tests required of intrinsically safe equipment, but in practice, the MSHA requirements parallel those of UL 913 and NFPA 493.

Traditionally, the term "safety factor," in the context of intrinsic safety, refers to a margin of safety in actual use, produced by using a higher current or voltage in approval testing than would be used in normal operation. The numerical safety factor is computed as the ratio of the product of the higher voltage and current to the voltage and current in normal operation. The safety factors related to the spark ignition characteristics of methane-air, propane-air, and ethylene-air mixtures remain unclear despite the widespread use of national standards for intrinsic safety. As the field of intrinsic safety advanced, it was found that spark ignition could be achieved at lower currents or voltages if the test electrode materials or geometry was altered. As more sensitive testing machines became possible, standards organizations adopted stricter test criteria without regard to the true safety factor of the test relative to the conditions of actual use.

Electronic equipment used in mining has evolved and become more complex. Solid-state electronics are used in all new applications for instrumentation, communications, environmental monitoring, etc. As the complexity of this equipment increases, so does its intolerance for the overvoltage or overcurrent conditions induced during routine intrinsic safety examinations. To conduct approval examinations of such sophisticated electronics, approval authorities usually test an equivalent circuit of the actual device. Such circuits are good representations of the device over some range of frequency, voltage, current, etc. However, the most desirable test would be one that supplies information on the unaltered circuit under consideration while providing a safety factor equivalent to that provided by conventional testing.

If safety factors are to be provided by some method other than increased current or voltage during testing, the behavior of the technique used to produce the safety factor must be thoroughly examined. Traditionally, the safety factor applied to MSHA intrinsic safety examinations has been 1.5 times rated energy at the point of test under the worst case, two-fault conditions. In other countries, the factor of 1.5 may be applied to voltage or current, not energy. The factor of 1.5 times has historically been used and has proven itself in practice to be adequate over the last 30 yr.

Safety factors could be produced in several ways aside from increasing the current or voltage. Zborovszky [1] reported that inconsistent results were achieved by attempting to use oxygen-enriched mixtures to provide safety factors. The author concluded that "...oxygen enrichment is too complicated and

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[2]Underlined numbers in parentheses refer to items in the list of references at the end of this report.

inaccurate..." The same report further concluded that increasing pressure during testing would provide a safety factor, but that this method suffers from increased experimental complexity, and pressure increases provide a safety factor that varies with circuit configuration.

In 1983, MSHA proposed to rewrite its intrinsic safety regulations in order to bring them up to the current state of the art and to incorporate several recent changes in MSHA policy regarding environmental monitoring systems. In support of this rewrite, MSHA requested that the Bureau of Mines investigate alternate ways of applying safety factors to modern electronic circuits in lieu of increasing current or voltage at the point of test. In response to that request, the Bureau tested spark ignition of methane-air, propane-air, and ethylene-air mixtures over a range of voltages and currents, to determine the safety factors associated with using more explosive gases in testing. Despite the widespread use of national and international standards for intrinsic safety, safety factors related to the spark ignition characteristics of the common test gases are uncertain. The purposes of the Bureau experiment were

1. To determine a statistical basis for the published spark ignition curves by conducting a large number of tests for resistive, inductive, and capacitive circuits in methane, propane, and ethylene;

2. To examine the relationship between the published spark ignition data and the curves derived from the experimental data;

3. To attempt to arrive at a good operational definition of "safety factor."

TEST PROCEDURES

STATISTICAL PROCEDURE

To present statistical data on spark ignition characteristics, a statistical method is needed that allows the gathering of a maximum amount of information with a minimum number of experiments. Such a method was developed at Princeton University (2) and refined by others (3-4). The method developed has become known within the Bureau as the Bruceton Up-Down Method for its subsequent use in the classification of explosives at the Bureau's Pittsburgh Research Center, at Bruceton, PA.

The Bruceton Up-Down Method is useful for dealing with quantities that are continuous but cannot be measured in a continuous fashion. An example is in testing the response of explosives to mechanical shock. In this type of test, a weight is dropped from a given height onto an explosive sample, and the mechanical energy released on impact with the sample may or may not ignite it. In either case, a new sample is used for each test. The weight is dropped from a new height, either higher or lower, depending upon the outcome of the previous experiment.

The testing height is clearly a continuous variable, but the test can be conducted only once on each sample. However, one may conclude with a certain degree of confidence based on the number of experiments that the critical height (the height that causes an explosion) is more or lesss than the height chosen for a particular test drop.

In testing the ignition of explosive gases, a similar situation exists. The gas mixture is closely controlled to its most explosive level, and the electrical test circuit is driven at a constant voltage or current. During a test, the gas mixture is constantly renewed. The ignition or nonignition of a gas mixture at a given voltage or current is dependent on mnay factors, such as electrode condition and material, ambient temperature, pressure, humidity, etc. If an ignition occurs at a specific voltage or current, a repeat test at the same value may not give ignition. The best that can be done in the case of explosive gas mixtures is to estimate a mean, a standard deviation, and confidence limits on the mean.

To apply the Bruceton Up-Down Method to spark ignition testing, the following procedure is used:

1. An appropriate test current (I) or voltage (V) is chosen for the first trial, based on the published spark ignition data.

2. An interval (d) between voltage or current test levels is estimated. This value should be approximately equal to the standard deviation. However, it is allowable for the interval to differ from the standard deviation by as much as 50%.

3. If an ignition occurs at the trial value (assume I in this example) then the next test will take place at I-d. If no ignition occurs, the next test will take place at I+d.

4. Each subsequent test will be run at a current level that is d units below the previous current if ignition occurs and d units above the previous current if ignition does not occur.

The procedure assumes that the shape of the distribution is approximately known. In this case, the current or voltage was assumed to be log normally distributed. When graphed on coordinates that are normally distributed along the X-axis, the plot of log current (or voltage) versus cumulative probability is approximately linear.

This statistical method has an important advantage over conventional methods. Since the Bruceton Up-Down Method tends to automatically concentrate testing about the mean, the number of experiments is greatly reduced. The one disadvantage is that the test current (or voltage) must be changed based upon the outcome of the previous experiment. In practice this proved to be only a minor inconvenience.

In order to accurately estimate the statistics in any experiment, one must generate a sufficient number of measurements to ensure that the confidence interval is acceptably small. The literature (2) cautions against using sample sizes smaller than 50 and recommends 100 as an appropriate size for most experiments. In this experiment, the number of trials to determine each mean was fixed at 100. Hence, about 50 experiments in any given series were ignitions and 50 were nonignitions. Since the distribution is approximately log normal, the mean and the median (50th percentile) have approximately the same value.

The mean may be estimated by the following equation:

$$\bar{X} = c + d \left[\frac{1}{N} \sum_i i n_i \pm \frac{1}{2} \right], \quad (1)$$

where $\bar{X}$ = mean value of ignition current (or voltage),

c = log of lowest current (or voltage) level,

d = log of increment between test levels,

i = internal number beginning with $c = 0$,

n_i = number of ignitions or nonignitions (whichever is fewest) occurring at the ith step,

and N = total number of ignitions or nonignitions (whichever is fewest).

The plus sign (+1/2) is used if the number of nonignitions is used and the minus sign if the number of ignitions is used.

The standard deviation is determined as follows. First calculate the intermediate variable, M:

$$M = \frac{\sum_i i^2 n_i}{N} - \left(\frac{\sum_i i n_i}{N} \right)^2. \quad (2)$$

The value of M is then used to find the value of the variable s, which is given graphically in reference 2 and may be approximated by the equation

$$s = (M + 0.04758)/0.62712, \quad (3)$$

where   s = correction factor for standard deviation for M > 0.4.

(For M < 0.4, consult reference 2 for the graphs.)

The sample standard deviation (S) may now be estimated as

$$S = (d)(s). \qquad (4)$$

The standard error of the mean (S_m) is estimated as

$$S_m = S(G)/(N)^{1/2}, \qquad (5)$$

where   G = a variable found graphically in reference 2 and estimated by the equation

$$G = -0.012793s^3 + 0.125471s^2$$

$$- 0.384361s + 1.288653. \qquad (6)$$

The percentile predictions and the confidence intervals may be calculated by standard statistical methods (5) once the mean, standard deviation, and standard error are known.

EXPERIMENTAL PROCEDURE

The experimental procedure used to estimate the statistical properties of the spark ignition curves centers around the standard procedures in UL 913. Each test was run with the most explosive gas-air mixture held within the limits specified by UL 913, as determined by on-line infrared analysis and occasional off-line chromatographic analysis. Four hundred revolutions of the International Electrochemical Commission (IEC) standard break-flash machine[3] (200 positive polarity and 200 reversed polarity) were run for each test. One hundred such tests were used as the basis for each graphical point, with the test current or voltage adjusted up or down based upon the outcome of the previous experiment. If an ignition occurred during the 400 revolutions, the time to ignition was recorded for future statistical work and the number of sparks inferred. If no ignition occurred, the number of sparks was assumed to be 1,600. The test was arranged so that about 50 ignitions and 50 nonignitions occurred in each set of 100 trials.

DISCUSSION OF RESULTS

RESISTIVE CIRCUITS

Figure 1 and table 1 show the data collected for resistive circuits in 8.3% methane-air, 5.3% propane-air, and 7.8% ethylene-air mixtures. The mean ignition currents are shown for voltages between 16 and 50 V dc since that is the range of greatest interest for mine environmental monitoring systems and other typical mine electronic systems. At voltages much less than 16 V dc in resistive circuits, the upper range of currents can easily exceed 4,000 mA, which may cause problems with hot-wire ignition in the standard breakflash machine.

Figure 2A shows the mean values for resistive circuits in 8.3% methane-air and

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[3]As described in IEC Standard 79-3.

TABLE 1. - Data for resistive circuits

Voltage, V dc	Mean, mA	99% confidence interval, mA	
		Lower limit	Upper limit
METHANE			
20......	3,130	2,934	3,738
30......	792	767	819
40......	410	386	436
50......	274	158	476
PROPANE			
20......	2,633	2,415	2,871
30......	551	534	568
40......	277	264	290
50......	182	172	193
ETHYLENE			
16......	3,548	3,273	3,847
20......	1,182	1,095	1,276
30......	341	325	359
40......	208	202	215
50......	153	146	161

10,000

CURRENT, mA

1,000

KEY
• Methane
■ Propane
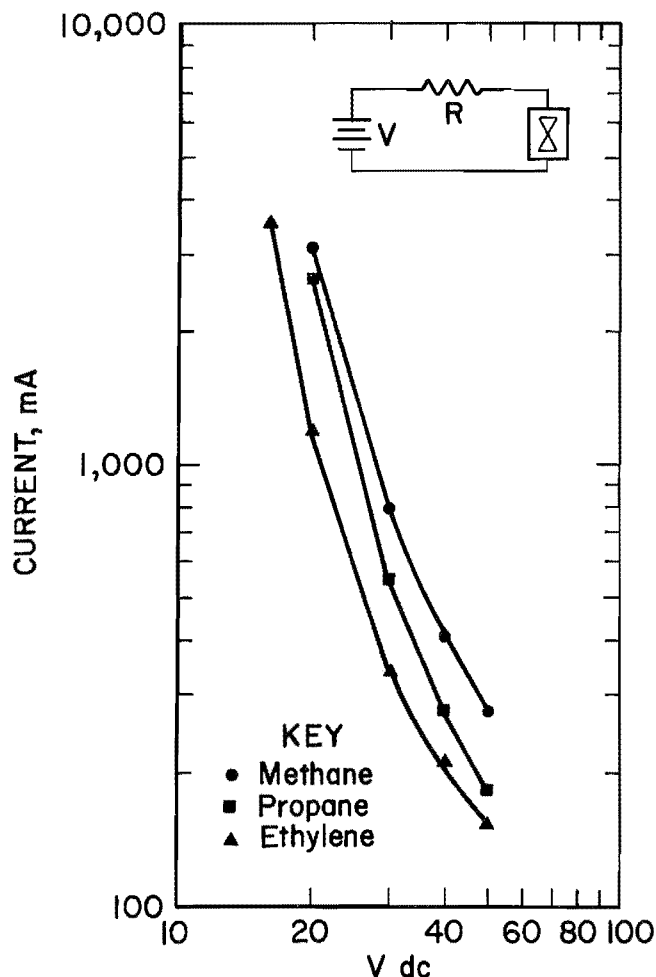▲ Ethylene

100
10   20   40 60 80 100
V dc

FIGURE 1.—Mean ignition current for resistance in 8.3% methane-air 5.3% propane-air, and 7.8% ethylene-air atmospheres.

their 99% confidence intervals. Figures 2B and 2C show mean value and 99% confidence interval data for circuits in propane-air and ethylene-air mixtures, respectively. The data for ethylene-air are complete down to 16 V dc because of ethylene's characteristically lower ignition level, whereas the data for propane-air and methane-air are complete only to 20 V dc. The 99% confidence intervals are "well behaved" (confined to an acceptably narrow region) about the means because of the relatively large body of data collected.

Figure 3A shows the relationship of the mean ignition currents in 8.3% methane-air and the curve as published

in UL 913. As can be seen, the data exceed the published curve by about 30% at 20 V dc, 10% at 30 V dc, 11% at 40 V dc, and 7% at 50 V dc. In fact, the published curve falls below the lowest observed ignition point at 20 V dc. The lowest data point at 50 V dc is about 25 mA below the published curve. Figure 3B shows the mean data for 5.3% propane-air mixtures, the published curve for propane, and the lowest observed data values. The lowest observed points fall below the published curve from 50 V dc to about 25 V dc, where the published data become lower. A similar situation occurs for 7.8% ethylene-air mixtures, shown in figure 3C.

The current at any percentile can be predicted using the mean and standard deviation calculated from the data. Figure 4 shows the mean value and the 10th and 90th percentile predictions for methane-air mixtures, as well as the range of the experimental data. The range of the data rarely exceeded the predicted 10th or 90th percentiles. In general, this situation held true for resistive circuits in all three gases. Considering that over 1,300 trials were run for resistive circuits alone, this is a glaring statistical anomaly. However, the Bruceton Up-Down Method is optimized to collect data about the mean and is, therefore, not a random sampling technique. Unless the distribution is very well behaved, small errors in the estimated standard deviation can give erroneous results when trying to predict extreme values, because very few data were actually collected in the extremes of the distribution. This situation will be corrected in work planned for the near future.

INDUCTIVE CIRCUITS

Figure 5 and table 2 show the data for inductive circuits at 24 V dc in 8.3% methane-air, 5.3% propane-air and 7.8% ethylene-air mixtures. The range of inductance values tested was from 500 µH to 600 mH. In figure 6A, the mean ignition
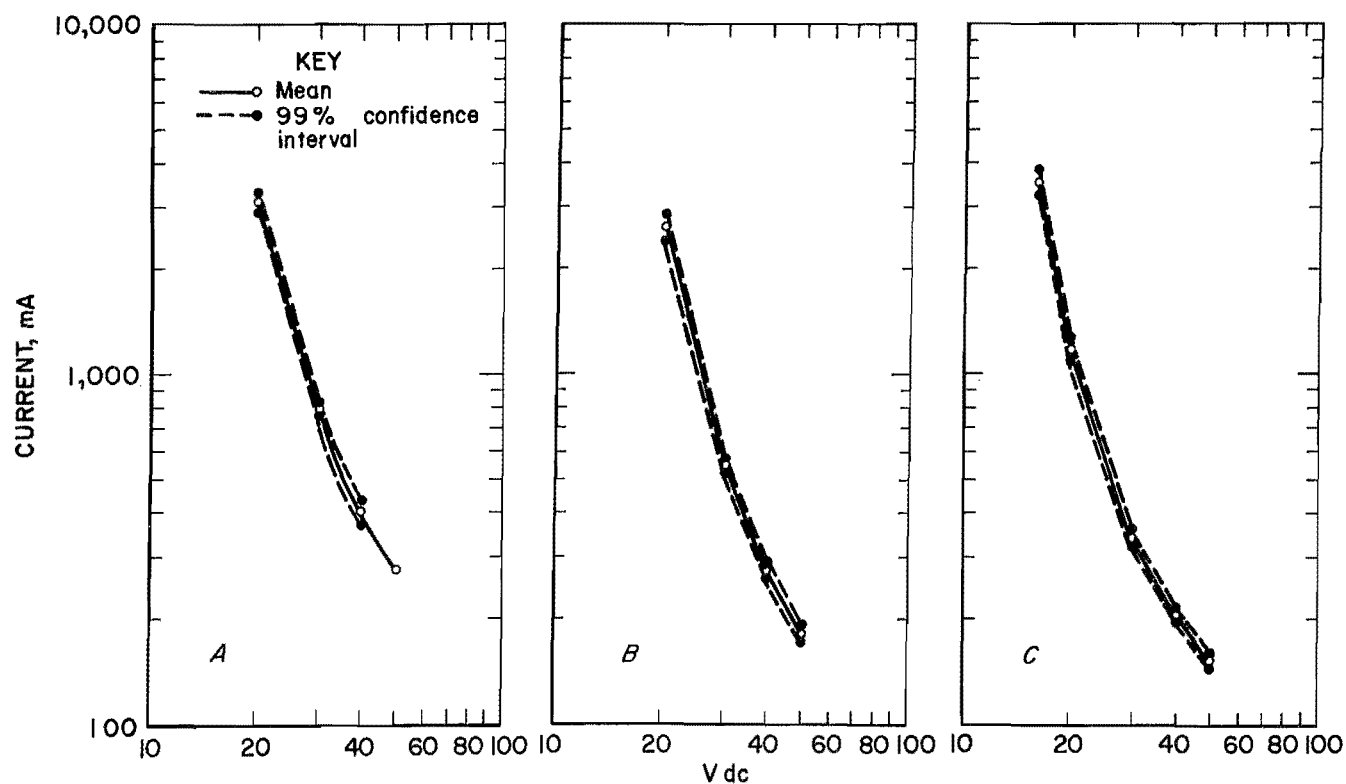
FIGURE 2.—Mean and 99% confidence interval for resistive circuits. *A*, In 8.3% methane-air; *B*, in 5.3% propane-air; *C*, in 7.8% ethylene-air.
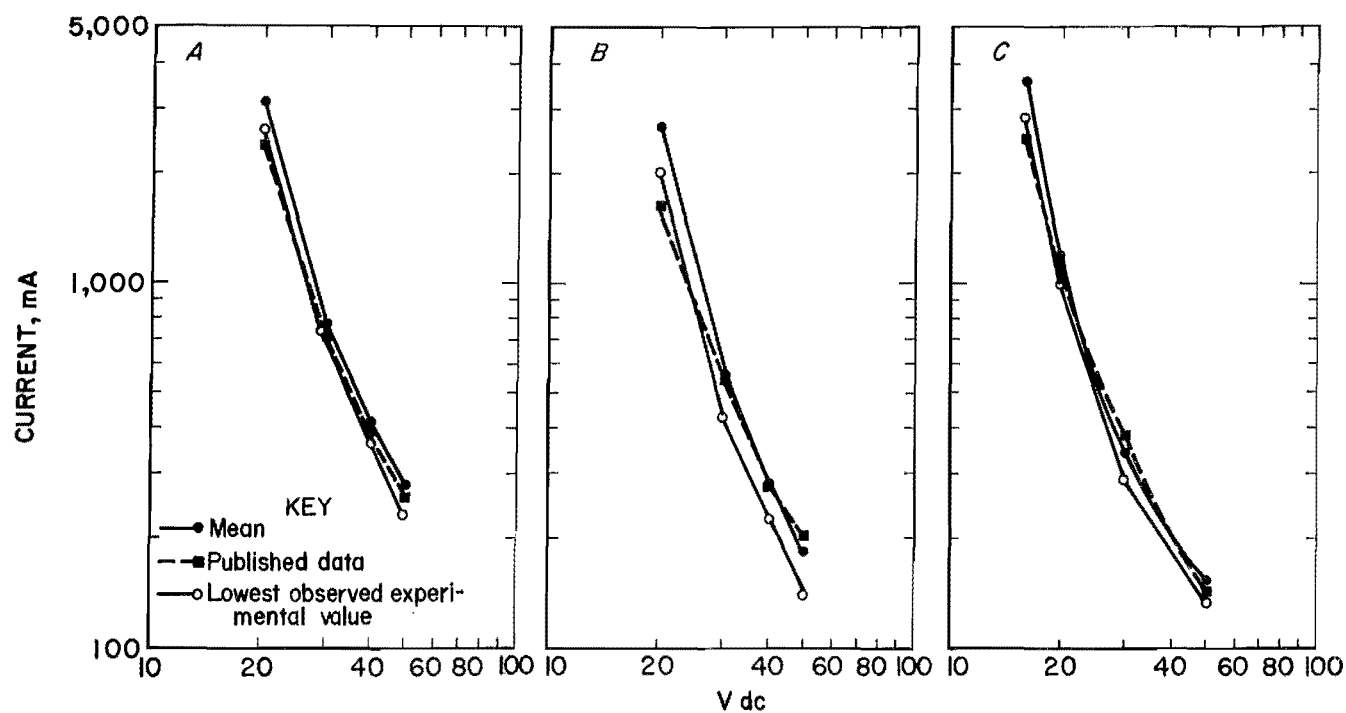

FIGURE 3.—Experimental versus published data for resistive circuits. *A*, In 8.3% methane-air; *B*, in 5.3% propane-air; *C*, in 7.8% ethylene-air.
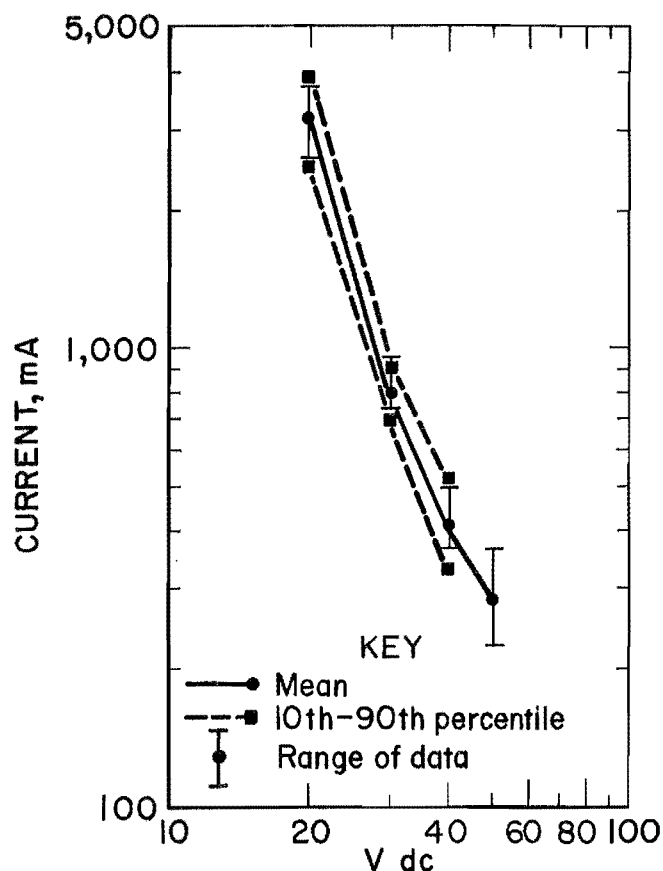
FIGURE 4.—Range of data for resistance in 8.3% methane-air.

FIGURE 5.—Mean ignition current for inductance in 8.3% methane-air, 5.3% propane-air, and 7.8% ethylene-air atmospheres at 24 V dc.

current for methane-air and its 99% confidence interval are shown plotted against inductance. The function is well behaved, and the confidence interval is very narrow. Likewise, figures 6B and 6C show very well behaved means and confidence limits for 5.3% propane-air and 7.8% ethylene-air, respectively. In each gas, tests at the 600-mH data point (100 trials) were repeated at 12 V dc to examine the effect of driving voltage on the mean ignition current. The mean ignition current was virtually identical at both 24 V dc and 12 V dc in all three gases.

Figures 7A, 7B, and 7C show the experimental and UL 913 ignition data for methane-air, propane-air, and ethylene-air, respectively. Figure 7A shows a close correlation between the published and empirical data in 8.3% methane-air. In figure 7B, however, the mean igniting
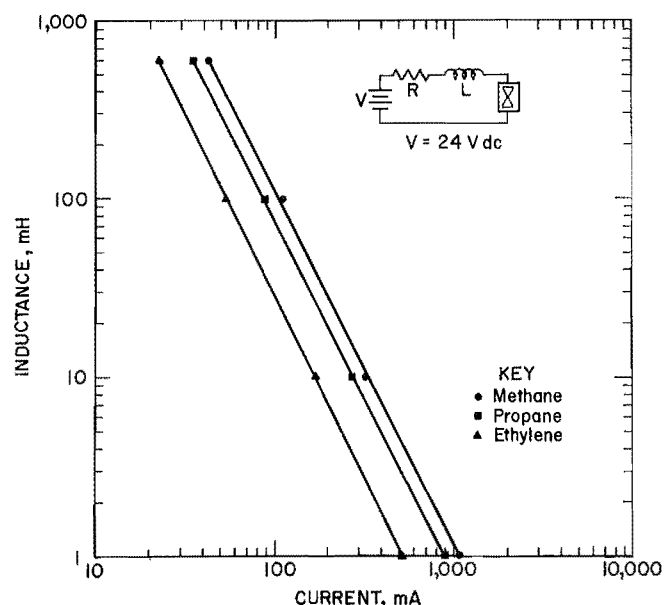
TABLE 2. - Data for inductive circuits (24 V dc)

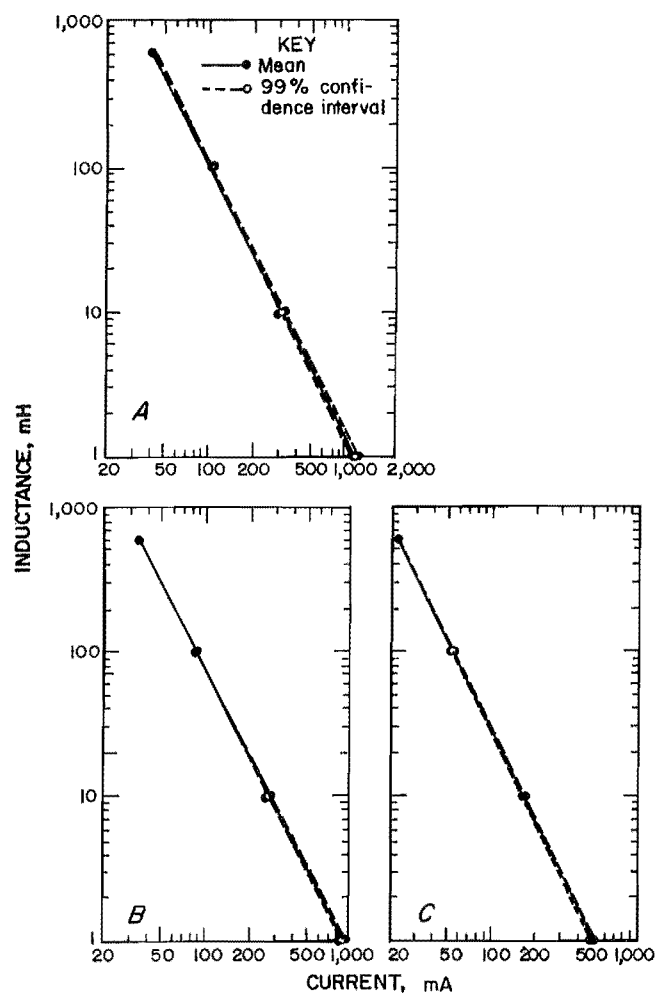| Induc- tance, mH	Mean, mA	99% confidence interval, mA	
		Lower limit	Upper limit
METHANE			
600.....	42	41.7	43.3
600[1]....	43	42.3	43.5
100.....	122	110	115
10......	318	314	322
1.......	1,092	1,074	1,111
0.5.....	1,314	1,260	1,371
PROPANE			
600.....	35	34	36
600[1]....	36	35	37
100.....	89	81	98
10......	276	269	284
1.......	905	881	929
0.5.....	1,196	1,095	1,307
ETHYLENE			
600.....	22.3	21.8	22.6
600[1]....	22.5	22.2	23.0
100.....	53	52	54
10......	167	165	170
1.......	511	501	521
0.5.....	599	569	631

[1]Tests run at 12 V dc.

FIGURE 6.—Mean and 99% confidence interval for inductive circuits. *A*, in 8.3% methane-air; *B*, in 5.3% propane-air; *C*, in 7.8% ethylene-air.

FIGURE 7.—Experimental versus published data for inductive circuits. *A*, in 8.3% methane-air; *B*, in 5.3% propane-air; *C*, in 7.8% ethylene-air.

current is up to 13% higher than that in the published data. Figure 7*C* shows that the mean igniting current and published current levels differ by about 8% at 1 mH, with the published current being higher. In each case, the discrepancies become more pronounced as the inductance decreases (the circuit becomes more resistive in nature). The inductive circuit test data maintained more reasonable confidence limits about the mean for low element values than did either the resistive or capacitive circuit data.

CAPACITIVE CIRCUITS

Experimental data were obtained for capacitors in 8.3% methane-air, 5.3% propane-air, and 7.8% ethylene-air mixtures. The capacitors used for the tests are described in table 3.[4] The capacitors were charged through a noninductive resistor whose value permitted charging

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[4]Reference to specific equipment does not imply endorsement by the Bureau of Mines.

for approximately five time constants be-
tween discharges. The breakflash machine
was run for 1,600 revolutions at 80 rpm
for each test, owing to the use of only a
single tungsten electrode. Polarity was
reversed at 800 revolutions.

The total discharge time for the test
circuit through the breakflash contacts
is also shown in table 3. This time was
measured using a storage oscilloscope in
parallel with the capacitor under test.

The energy contribution from the power
supply (P, in watts) during the discharge
time (t, in seconds) can be estimated by
assuming a rectangular discharge pulse at
the mean ignition voltage for the dura-
tion of the discharge as

$$E = Pt = \frac{V^2 t}{R}, \qquad (7)$$

where   E = total energy contribution
             from power supply, J;

        V = mean ignition voltage, V dc;

and   R = current-limiting resistance
             value (from table 3), ohms.

This relation yields the results shown in
table 4. Thus, in all cases, the energy
contributed by the power supply ($V^2 t/R$)
during the capacitor discharge period is
less than 1% of the mean stored energy
required for ignition ($1/2\ CV^2$).

Figure 8 shows the mean ignition volt-
age curves obtained in 8.3% methane-air,
5.3% propane-air, and 7.8% ethylene-air
mixtures. It is interesting to note in
figure 8 that there is little difference
in the test data for 8.3% methane-air and
5.3% propane-air mixtures above 10.3 µF.
In fact, the mean ignition voltages tend
to converge as the value of capacitance
exceeds 100 µF. Table 5 shows that the
statistical confidence of the mean igni-
tion voltage is very good for capacitance
values of 10.3 µF and above. The mean
ignition voltage for a capacitance value
of 1.2 µF is unreliable since its confi-
dence limits are very large. The 99%
confidence limit about the mean for each
test gas is shown if figure 9.

Figure 10 compares the UL 913 spark
ignition curve and test data for 8.3%
methane-air mixtures. The published

TABLE 3. - Capacitor test circuit characteristics

Capacitor	Capaci-tance, µF	Voltage, V dc	Time con-stant, µs	Resistor, kohm	Discharge time,[1] µs
Mallory:					
TC56.........	1.2	250	0.104	87.0	0.7
TC50100.....	1,330	50	.100	.075	500
Sprague:					
TE1407......	10.3	100	.103	10.0	3.5
TE1211......	106	25	.106	1.0	200

[1]Measured from test circuits.

TABLE 4. - Ignition energy contribution from power
supply ($V^2 t/R$) versus ignition energy ($1/2\ CV^2$)

(Methane-air mixture)

Capacitance...............µF..	1.2	10.3	106	1,330
Voltage...................V dc..	124	36.8	19.9	12.9
Time constant.............µs..	0.7	3.5	200	500
Resistor..................kohm..	87.0	10	1	0.075
Energy ($V^2 t/R$).............µJ..	12.4	47	79	1,100
Energy ($1/2\ CV^2$)...........mJ..	9.2	7.2	21	111

FIGURE 8.—Mean ignition voltage for capacitance in 8.3% methane-air, 5.3% propane-air, and 7.8% ethylene-air atmospheres.

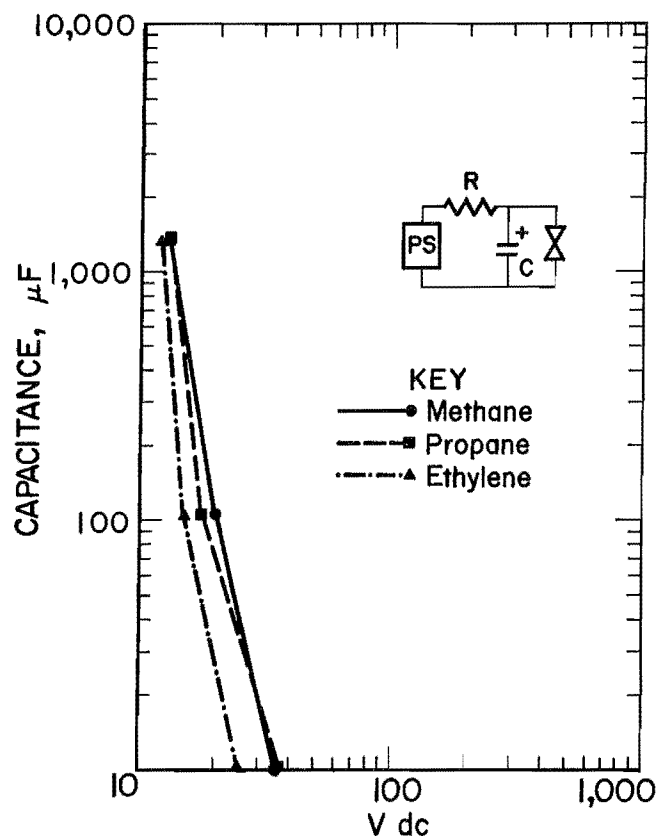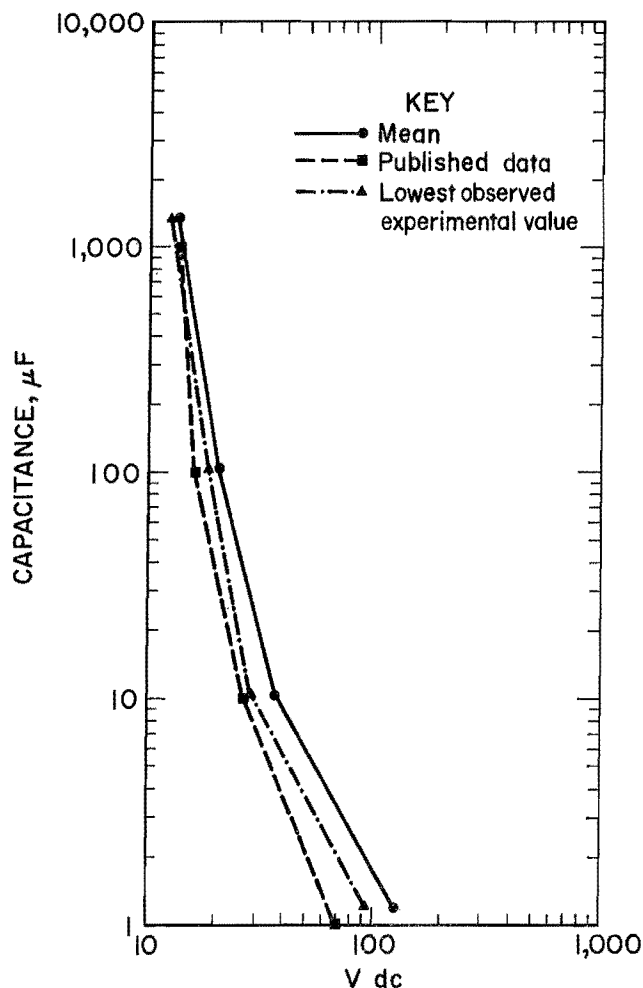FIGURE 10.—Capacitance in 8.3% methane-air—experimental versus published data.
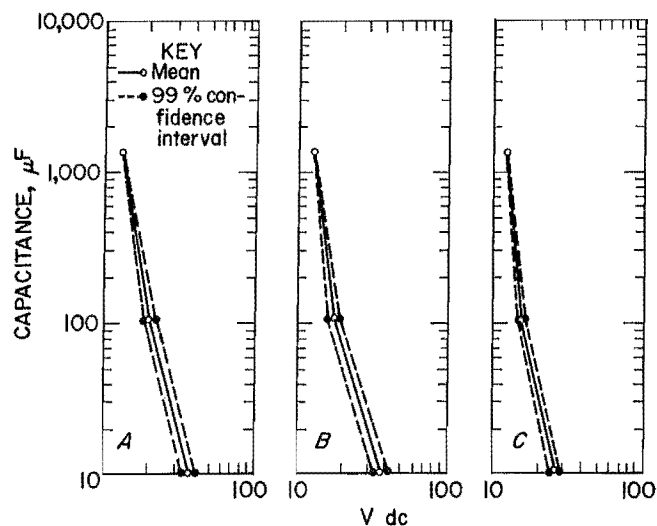
FIGURE 9.—Mean and 99% confidence interval for capacitive circuits. A, In 8.3% methane-air; B, In 5.3% propane-air; C, in 7.8% ethylene-air.

curve more closely approximates the lowest observed ignition values than the mean. Once again, the empirical values below 10.3 µF lack sufficient statistical confidence from which to draw any firm conclusions.

The mean and lowest observed ignition energies for capacitive spark ignition are tabulated in table 6. As can be seen, the process of capacitor spark ignition in the IEC breakflash is relatively inefficient compared with the minimum ignition energies for methane, propane, or ethylene from the literature (6). It should be reemphasized here that this experiment was not optimized to find the minimum ignition energies but to

determine the mean value. The minimum spark ignition energies found in the literature are significantly lower than the lowest observed values cited here.

SAFETY FACTOR DETERMINATION

In the United States, the generally accepted concept for applying safety factors to intrinsically safe circuits is to increase the energy at the point of test by a factor of 1.5 over the conditions of use. This level of safety factor has been shown through long experience to provide a satisfactory margin of error against variations in test conditions, part tolerances, etc. The mean value of the ignition variable is used for each circuit element to calculate a relative safety factor when testing in a more easily ignited test gas.

For a resistive circuit, the energy may be defined as

$$E_R = VIt, \qquad (8)$$

where E_R = mean ignition energy, J;

   V = mean ignition voltage, V dc;

   I = mean ignition current, A;

and t = discharge time of the test circuit through the IEC breakflash contacts, s.

TABLE 5. - Data for capacitive circuits

Capacitance, µF	Mean, V dc	99% confidence interval, V dc	
		Lower limit	Upper limit
METHANE			
1.2.....	124	NA	NA
10.3....	36.8	33.4	40.5
106.....	19.9	19.1	20.7
1,330...	12.9	12.9	13.0
PROPANE			
1.2.....	161	NA	NA
10.3....	35.3	32.4	38.4
106.....	17.7	17.1	18.5
1,330...	13.0	12.8	13.2
ETHYLENE			
1.2.....	138	NA	NA
10.3....	25.1	23.0	27.3
106.....	14.8	14.4	15.3
1,330...	11.7	11.6	11.8

NA Not available.

The average resistive discharge time was measured as approximately 5 µs, independent of the driving voltage and gas mixture. To compare methane and propane ignitions at a given mean current,

$$\text{safety factor} = \frac{E_{RM}}{E_{RX}} = \frac{V_m I_m t}{V_x I_x t}, \qquad (9)$$

where E_{RM} = mean ignition energy for methane, J;

   E_{RX} = mean ignition energy for comparison gas, J;

   $V_x = V_m$ = comparison voltage, V dc;

   I_m = mean ignition current for methane, A;

   I_x = mean ignition current for comparison gas, A;

and t = discharge time, s.

Since the mean currents are being compared at a constant voltage and constant discharge time,

$$\text{safety factor} = \frac{I_m}{I_x}. \qquad (10)$$

Therefore, the safety factor for resistive circuits is the ratio of the mean currents along lines of constant voltage;

TABLE 6. - Ignition energy ($1/2 \ CV^2$)

Capacitance......µF..	1.2	10.3	106	1,330
Mean ignition energy, mJ:				
Methane.............	9.2	7.2	21	111
Propane.............	15.5	6.4	17	112
Ethylene............	11	3.2	12	91
Lowest observed ignition energy, mJ:				
Methane.............	5.6	4.1	18	102
Propane.............	7.4	4.5	15	102
Ethylene............	5.6	2.3	10	87

TABLE 7. – Safety factors for resistive circuits

Constant voltage..........V dc..	20	30	40	50
Mean ignition current, mA:				
Methane (I_m)...................	3,130	792	410	274
Propane (I_p)...................	2,633	551	277	182
Ethylene (I_e)...................	1,182	341	208	153
Safety factor:				
Methane-propane (I_m/I_p).......	1.19	1.44	1.48	1.51
Methane-ethylene (I_m/I_e)......	2.65	2.32	1.97	1.79

safety factors are shown in table 7 and in figure 11.

In inductive circuits, the energy may be defined as

$$E_L = 1/2\ LI^2, \qquad (11)$$

where E_L = mean ignition energy, J;

        L = test inductance, H;

and   I = mean ignition current, A.

The inductive test circuit discharge time through the IEC breakflash was measured and found to be relatively constant at 0.25 µs for the range of inductance values tested.

Since the mean inductive ignition currents are independent of voltage, the safety factor for inductive circuits can be computed as

$$\text{safety factor} = \frac{E_{LM}}{E_{LX}} = \frac{1/2\ LI_m^2}{1/2\ LI_x^2}$$

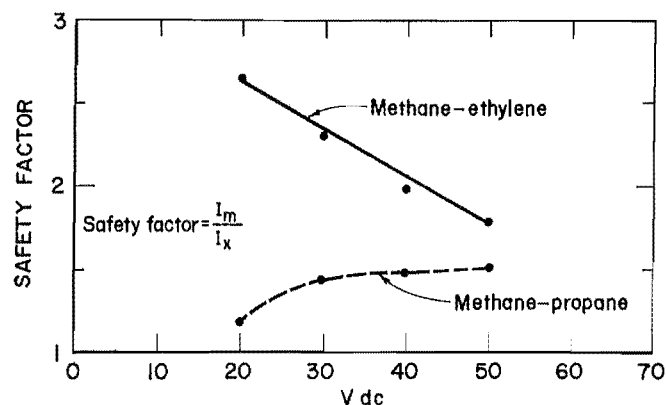$$= \left(\frac{I_m}{I_x}\right)^2, \qquad (12)$$

where E_{LM} = mean ignition energy, methane, J;

     E_{LX} = mean ignition energy, comparison gas, J;

     L = test inductance, H;

     I_m = mean ignition current at L, methane, A;

and I_x = mean ignition current at L, comparison gas, A.

The inductive safety factors thus computed are shown in table 8 and in figure 12.

For capacitive circuits, the mean ignition energy may be defined as

$$E_c = 1/2\ CV^2, \qquad (13)$$

where E_c = mean ignition energy, J;

     C = test value of capacitance, F;
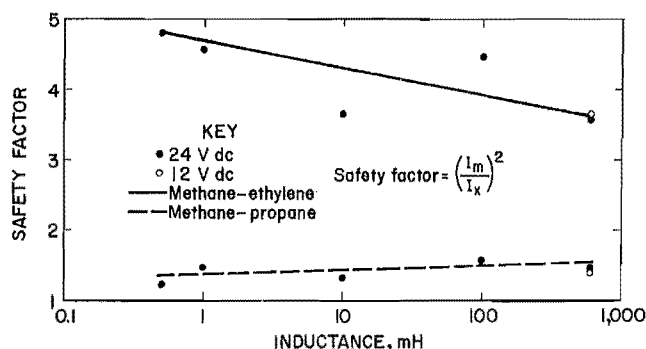
and   V = mean ignition voltage, V dc.

FIGURE 11.—Resistance safety factors.

FIGURE 12.—Inductance safety factors.

TABLE 8. - Safety factors for inductive circuits at 24 V dc

Inductance.....................mH..	0.5	1	10	100	600	[1]600
Mean ignition current, mA:						
Methane (I_m)....................	1,314	1,092	318	112	42	43
Propane (I_p)....................	1,196	905	276	89	35	36
Ethylene (I_e)...................	599	511	167	53	22.3	22.5
Safety factor:						
Methane-propane $(I_m/I_p)^2$.......	1.21	1.46	1.33	1.58	1.44	1.43
Methane-ethylene $(I_m/I_e)^2$......	4.81	4.57	3.62	4.47	3.55	3.65

[1]Tested at 12 V dc.

TABLE 9. - Safety factors for capacitive circuits

Capacitance.....................µF..	1.2	10.3	106	1,300
Mean ignition voltage, V dc:				
Methane (V_m)....................	124	36.8	19.9	12.9
Propane (V_p)....................	161	35.3	17.7	13.0
Ethylene (V_e)...................	138	25.1	14.8	11.7
Safety factor:				
Methane-propane $(V_m/V_p)^2$........	[1]0.59	1.09	1.26	0.98
Methane-ethylene $(V_m/V_e)^2$.......	[1]0.81	2.15	1.81	1.22

[1]Based on mean voltages of low statistical confidence.

The safety factor of a capacitive test circuit can be computed as

$$\text{safety factor} = \frac{E_{cm}}{E_{cx}} = \frac{1/2 \; CV_m^2}{1/2 \; CV_x^2}, \quad (14)$$

where E_{cm} = mean ignition energy, methane, J;

E_{cx} = mean ignition energy, comparison gas, J;

C = test capacitance, F;

V_m = mean ignition voltage, methane, V dc;

and V_x = mean ignition voltage, comparison gas, V dc.

The capacitive safety factor thus becomes

$$\text{safety factor} = \left(\frac{V_m}{V_x}\right)^2 \quad (15)$$

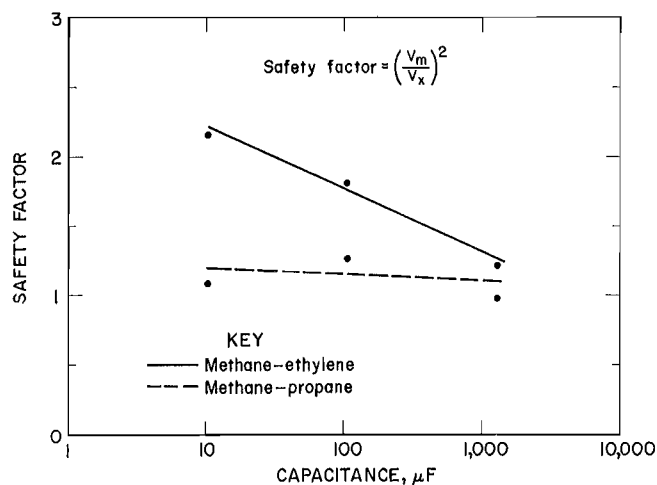and is shown in table 9 and figure 13.

FIGURE 13.—Capacitance safety factors.

CONCLUSIONS

To facilitate estimating the safety factors provided by testing with more easily ignited gases rather than higher currents or voltages, the Bureau experimentally established spark curves that yield a 50% probability of ignition during a standard intrinsic safety test in the IEC breakflash apparatus. Propane-air, ethylene-air, and methane-air mixtures were tested over a range of voltages and currents, to establish safety factors for testing intrinsically safe equipment.

However, the safety factor provided by testing in a more explosive gas is not constant with voltage or current. For example, the safety factor for ignition in methane-air versus propane-air in a resistive circuit increases from 1.19 to 1.51 between 20 and 50 V dc while the safety factor for ignition in methane-air versus ethylene-air decreases from 2.65 to 1.79 over the same range. The safety factors obtained for inductive and capacitive circuits show similar trends. Applying safety factors through the use of alternate test gases is not a straightforward procedure and, therefore, is not recommended.

The statistical basis for the curves published in UL 913 has been clarified somewhat by this study, in that the relationship of curves to the mean values of the ignition variable has been quantified. Minimum ignition currents (or voltages) cited in other literature are substantially lower than results presented here, which are the mean values of ignition currents or voltages. The differences between the mean and minimum ignition values are especially large in the capacitor data where the voltages are highly variable at a capacitance of 1.2 μF. In data having a small standard deviation, the mean and minimum ignition values are rather close.

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